SEISMIC WAVE PROPAGATION STUDIES

Final Report

1 June 1966 Through 30 May 1970

Prepared for
Geophysics Division
Air Force Office of Scientific Research
Arlington, Virginia 22209

By
D. E. WILLIS
P. L. JACKSON
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September 1970

GEOPHYSICS LABORATORY
Willow Run Laboratories
INSTITUTE OF SCIENCE AND TECHNOLOGY

Sponsored by
Advanced Research Projects Agency
Nuclear Monitoring Research Office
Project VELA UNIFORM
ARPA Order No. 292, Amendments 32 and 37

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Ann Arbor, Michigan

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FOREWORD

The Geophysics Laboratory of the Willow Run Laboratories of the University of Michigan's Institute of Science and Technology has been engaged in a program of research into the various aspects of seismic and acoustic wave propagation studies since 1952. This research has included theoretical studies, field measurement programs, data analyses, and the design and construction of special equipment to implement the field and laboratory requirements.

This work has been sponsored in the past by the U. S. Army Signal Corps, the Office of Naval Research, the Air Force Cambridge Research Laboratories, the Air Force Technical Applications Center, the Air Force Office of Scientific Research and the National Science Foundation. The work reported herein covers a four year time period from 1 June 1966 through 31 May 1970 and was supported by the Advanced Research Projects Agency, ARPA Order No. 292, Amendments 32 and 37, and was monitored by the Air Force Office of Scientific Research under Contract AF49(638)-1759.

This report is written to fulfill contractual requirements for a final report. Previous technical reports and scientific journal articles have presented a large portion of the research sponsored by this contract, and the data contained in these reports and articles will only be referred to in this report.

ABSTRACT

A new method of simulating seismic rays, computing travel times, and approximating amplitudes in earth models has been developed. The digital computer is used to model a spherical or a flat earth. [illegible] of three-dimensional models are employed, and regions of the model are defined for the velocity distribution to be represented either as an analytical function or sampled on a grid. Rays are plotted by computer and travel times are calculated to any desired degree of accuracy for the model under consideration. The method can be used for heterogeneous models, and includes computation of multiple reflections. Travel times have been obtained for a model of a cross-section underlying LASA. In a supplement (8071-33-F$_1$) to this final report this simulation method is described and illustrated in detail. The supplement is based upon a doctoral dissertation on this method by P. L. Jackson.

In 1967 the investigation of optical processing was terminated. Initiated in 1961, the investigation was conducted to explore the application of coherent optical processing to seismic analysis. Its use was found to lie primarily in oil exploration seismology. The results of the optical investigation were presented in several journal articles during the period 1963–1968.

A data processing capability specifically intended for the study of the S-wave particle variations across LASA was built on this contract. The LASA data processor, which existed in this laboratory for the optical analyses of LASA data was modified to interface with this laboratory's PDP-8 computer. This would allow unlimited computing at no cost and immediate man-machine interaction. An inhouse wiggly line output device was modified to print out the processed and unprocessed three-component data. This capability was not used due to funding limitations.

Microseismic investigations in connection with JORUM indicated that the firing of a large yield underground shot did not produce any

[illegible] A pronounced [illegible] in frequency content, [illegible] amplitude and wave [illegible] duration was observed around the [illegible] that can be explained in part by complicated local geology [illegible].

Travel time studies of PKP and P were used to determine the surface configuration of a portion of the earth's core. An extensive study was made on the attenuation and travel times of seismic waves in the Eastern United States. Theoretical studies were made to determine the scattering effects of plane elastic waves by surface imperfections and to determine the sources of error in the time-term method in refraction seismology.

Spectral studies were made of underground nuclear shots and earthquakes recorded at teleseismic, regional and near distances. An additional study was made of the characteristics of seismic background noise recorded on the bottom of Lake Superior.

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[illegible], in handling critical [illegible], in developing the method for high accuracy, [illegible] in [illegible] both a spherical and a flat earth, and in making the program general.

The method is described in detail with listed computer programs in a supplement to this final report. Computer plotted rays for several different models are illustrated in the supplement.

During this investigation the choice of continuing the development of the method rather than of applying the method in detail to a specific region was made several times. It was believed that it would be more useful to extend and perfect a diagnostic tool that the seismological profession could use, than to halt its development to thoroughly investigate a velocity distribution in a particular region. Also, the further development of the method included the increasing of its accuracy.

A preliminary investigation was performed with a model of LASA as found in Greenfield and Sheppard (19[illegible]). Their model of a NW-SE cross-section through LASA was used with incident plane waves, in the manner that is illustrated in Figures 3 and 4 of Report No. 8071-33-F_1. Seventy-five rays, each at angles corresponding to deltas of 10°, 19°, 32°, 45°, and 56°, were initiated. From the average travel times differences in a region 20 km on either side of site AO, the following values for $dT/d\Delta$ were found:

Δ(deg)	$dt/d\Delta$(sec/deg)
10	8.63
19	7.55
32	6.92
45	6.62
56	6.22

This preliminary test resulted in dT/dΔ values substantially lower (from .0[illegible] sec to .[illegible] sec) than those actually measured at the Montana LASA [illegible]. These discrepancies could be due to the choice of [illegible] km/sec for the reference velocity which was used to compute the initial time of the incident ray or the conversion to [illegible] from incident angle of plane wave in the [illegible] km/sec layer. The computer cost was 1.3 cents for each ray computed, including print out of location of emergence of ray, travel time, and approximate relative amplitude.

2.2. OPTICAL ANALYSIS TECHNIQUES

A thorough investigation of optical processing for seismic data was concluded in 1967. This investigation was initiated in 1961 under AFOSR Contract AF 49(638)-1078, and continued under AFOSR Contract AF49(638)-1170. This investigation was the first to apply coherent optical processing to seismics. It stimulated many other investigations which resulted in the application of optical processing to oil exploration seismology, and the marketing of commercial instruments for such processing. However, its application to VELA UNIFORM problems was not sufficiently useful to continue the investigation. Optical processing was made less attractive by the advent of the fast Fourier transform programs for the digital computer.

At the inception of this contract in 1966 it was planned to apply both coherent and non-coherent optical processing to Montana LASA data. A data converter was constructed to select data channels from LASA digital tapes for recording on variable-density films. This converter was constructed and films were made. However, the decision by the Sponsor to create the Seismic Analysis Center made the optical approach obsolete in the opinion of the principal investigator and the Sponsor. The investigation was therefore terminated. The LASA data converter has been used subsequently to select and re-record LASA data for other investigations within the Geophysics Laboratory.

FILTERING—S-WAVE STUDIES

During the contract period work has progressed toward an understanding of S-wave particle motion variations across LASA. Due to limited funds it was decided to do the necessary signal analysis on the PDP-8/I digital computer that is in our laboratory and available at all times at no cost. Although this computer is much smaller than the IBM 360/67 available on campus it offers the additional advantage (other than no cost) of immediate man-machine interaction even when the data is on tape.

The input for the PDP-8/I is the LASA data processor and it had to be interfaced with the PDP-8/I. This work has proceeded well and is described below.

An interface was designed and constructed between the LASA data converter and the PDP-8/I digital computer. Via this interface, under computer program control, LASA digital data can be stored in the PDP-8/I memory for digital processing. The LASA data converter assembles the digital seismometer samples from the bytes on magnetic tape and, at the proper time, the computer accepts that sample. Since the PDP-8/I is a 12-bit word length machine, a switch setting selects the 12 most significant bits, the 12 least significant bits or the "middle" 12 bits of the 14-bit LASA word.

Data from either LASA high rate or low rate tapes may be stored via the interface. A maximum of 50 words, in either format, may be selected on the LASA data converter and those words, taken in increasing numerical order in each record, will be stored in sequential addresses in the PDP-8/I memory. The number of samples to be stored may be controlled either by the computer program or by the number of records the LASA data converter reads, whichever method is appropriate. Available computer memory space governs the total number of LASA samples that may be stored.

To check the total system LASA data tapes were required. Since great delays were encountered in receiving these tapes as has been discussed, a request was made directly to M. Nafi Toksoz of Planetary Sciences Department at M.I.T., to get a composite tape and the S waves used by John W. Fairborn (1969) in recent paper. This data was received promptly and the total LASA data processor/PDP-8/I system is now ready.

No output device displaying wiggly-lines was available for the PDP-8/I. Again due to limited funds none could be purchased on this contract, therefore, inhouse funds are providing a three-channel analog output capability for the system.

Despite the fact that this data processing system is now ready for use at no cost, work was terminated due to depleted contract funds. Additional funding would be required to complete the anticipated work. Since we are only now ready to begin the actual S-wave analysis and since the necessary computing can now be done at no cost it is sincerely hoped that additional funding can be obtained.

2.4. SPECIAL STUDIES

2.4.1. MICROEARTHQUAKE INVESTIGATIONS. The Geophysics Laboratory operated a tripartite net of three-component short-period seismograph stations for a period of two weeks before the JORUM underground nuclear shot and for three weeks after to study the microseismic activity in a tectonically active area northeast of the shot. The results of this study are contained in a paper entitled, "Microearthquake Studies in Connection with the JORUM Underground Nuclear Detonation," by D. E. Willis that has been submitted to the Bulletin of the Seismological Society of America for publication.

2.4.2. DECOUPLING EXPERIMENT. Five short-period seismograph stations were operated at the Nevada Test Site to record DIAMOND DUST, a low yield nuclear device that was detonated in a spherical cavity to determine the feasibility of using thermomechanical techniques for decoupling seismic energy. Excellent results were obtained from this experiment. A technical report describing these results will be published as a supplement to this report (8071-33-F_3/3620-1-T) that will present the results of this test.

2.4.3. CONFIGURATION OF THE SURFACE OF THE EARTH'S CORE FROM PcP TRAVEL TIMES. A comprehensive study (doctoral thesis--C. Bufe) was made using PcP and P travel times to ascertain the configuration of the surface of the earth's core. Nuclear and high explosive sources were used in this study. Travel-time residuals from the Taggart-Engdahl (1968) tables were determined for PcP-P time intervals and for PcP travel times, corrected for station and source terms. Corrections were also made for elevation of source and station and for ellipticity, excluding the core ellipticity term.

The distribution of the data would not allow the application of conventional spherical harmonic analysis techniques on the inferred variation of the core radius. Hence a modified spherical harmonic analysis method was devised to smooth the data and to estimate the shape of the core. The variation of the core radius was determined to be ±10 km using this technique.

This investigation is described in detail in a supplement (8071-33-F_2) to this final report. The supplement is based upon a doctoral dissertation by C. G. Bufe.

2.4.4. OTHER STUDIES. A number of other studies were conducted during the course of this contract. These have been reported in journal articles, University of Michigan technical reports and at scientific meetings. These reports are listed below and abstracts are reproduced in Appendices I-III:

"A Long Range Reversed Seismic Refraction Profile in the Eastern U. S." by D. E. Willis and J. T. Wilson.

"Seismic Radiation from SHOAL" by C. G. Bufe and D. E. Willis.

"Seismic Noise on the Bottom of Lake Superior" by D. E. Willis.

"An Investigation of Seismic Wave Propagation in the Eastern U. S." by D. E. Willis.

"Scattering of Plane Elastic Waves by Surface Imperfections" by I. K. McIvor.

"High Frequency Teleseismic Energy From Aleutian Sources" by C. G. Bufe and D. E. Willis.

"An Investigation Into the Time-Term Method in Refraction Seismology" by Leon Reiter.

"A Note on Short-Period Seismic Spectral Ratios" by C. G. Bufe and D. E. Willis.

"Near Earthquake Spectra" by C. G. Bufe and D. E. Willis.

"A Note on the Anna, Ohio Earthquake of July 26, 1968" by D. E. Willis and James T. Wilson.

3
CONCLUSIONS AND RECOMMENDATIONS

3.1. DIGITAL RAY TRACING

A versatile tool has been developed for the scientific investigation of velocity distributions in the earth. Any conceivable velocity distribution can be modeled, and by simulation the travel times can be compared with actual travel times to determine the validity of the model. The simulation applies wherever geometrical ray approximations are useful.

It is recommended that

1. The programs be made as usable as possible for other investigators and funds for providing cards, programming help, and dissemination to other investigators be provided.

2. An extensive investigation of models of the underlying structure of LASA and other pertinent regions be initiated.

3. The method be extended to include mode conversion and Zoeppritz's equations.

4. Travel times and positions are known, therefore the basic information for computing diff tive effects is available, and should be investigated.

3.2. OPTICAL ANALYSIS TECHNIQUES

This investigation has been terminated.

It is recommended that no further effort be made in this direction. Subsequent to the investigation reported here, there have been many investigations of optical analysis, primarily by the oil exploration companies. Duplicating these efforts would be redundant. One extension of this technique is holographic seismology, which has been investigated in three laboratories for approximately five years. Results will be disseminated if holography is useful for seismics. In the opinion of the principal investigator there is little hope that holography will be useful, except possibly heuristically in giving new insights which might result in new digital computation techniques.

3.3. MODE FILTERING——S-WAVE STUDIES

Although several array studies (Fairborn, 1969; Whitcomb, 1969) of S waves have been made it appears that no work has been published concerning explosion generated SH waves propagating across LASA. Work currently being done by Turpening and Pomeroy shows that indeed earthquake/explosion discrimination can be performed with SH wave magnitudes. This work is being done with WWSSS and the Canadian network. Such discrimination should be attempted with long period LASA data.

However, the SH wave work being done now by Turpening and Pomeroy is restricted to large explosions (Benham, Faultless, Boxcar, and Greeley) and comparable sized earthquakes. The problem lies with the explosions. Since they generate relatively little SH wave radiation it is very difficult to find stations situated at distances large enough to separate the "weak" SH waves from the surface wave train yet operating at magnifications large enough to provide reasonable measurements. Because of this problem the work of Turpening and Pomeroy cannot be applied to smaller magnitude explosions.

Therefore, it is recommended that

1. Long period LASA data be used to study the discrimination capabilities of SH wave magnitude vs. P wave magnitude diagrams.

2. Using the computer/LASA playback system developed at the Geophysics Laboratory, investigate array and/or three-component signal processing techniques to enhance weak SH arrivals from small explosions. Such a study should make use of not only LASA data but also NOSAR and ALPA data. ALPA in fact lies at a good distance from NTS such that the SH arrivals would be separated from the surface wave trains.

3.4. SPECIAL STUDIES

3.4.1. MICROEARTHQUAKE INVESTIGATIONS. The local seismic activity in three active fault areas some 60 to 100 km from the JORUM event showed no significant difference before or after the event, thus demonstrating that the shot did not generate any earthquakes in the area of these temporary stations. High record gains were used and the stations were operated continuously so no significant events should have gone undetected.

Locally very small events were detected at all stations that had spectral peaks as high as 80 Hz. The Groom Lake station had the highest number of these events. At this site the occurrence of these events showed a strong diurnal effect.

3.4.2. DECOUPLING EXPERIMENT. The seismic measurements of DIAMOND DUST indicated that considerable decoupling was achieved. The absolute efficiency of the decoupling, however, cannot be determined with any confidence without additional tests. The five stations used to record this event should be reoccupied for any additional shots in this area. The ideal case would be to fire a tamped nuclear shot of the same yield. This would allow highly accurate decoupling measurements.

Smaller yield tamped HE shots and a nuclear shot of the same yield fired in the same sized cavity without the heat sink would provide very useful data for computing the efficiency of the DIAMOND DUST experiment.

Current studies are being made of data obtained from the U.S.C. & G. S. on the HUDSON MOON and DIESEL TRAIN shots. While these are larger events, they were recorded at comparable distances to our DIAMOND DUST recording stations and the event was fired in tuff. Hence the data will be useful for scaling purposes and perhaps a better estimate can be made on the decoupling efficiency.

3.4.3. OTHER STUDIES. The conclusions on the other studies may be found in the published reports referenced in Appendix I-III.

4
EQUIPMENT PURCHASES AND DEVELOPMENT

Listed below are all of the capital items of equipment purchased under this contract.

1 Sprengnether Recorder (Purchased August 1969)

Equipment developed under this contract include the following:

Intermediate-depth well seismic monitoring system

LASA data converter

Optical data analyzer

Transistorized seismic preamplifiers

DC Line amplifiers

Polyfilters.

The initial design on the above equipment was done under sponsorship of previous AFOSR contracts but further developments, improvements and some construction was accomplished under this contract.

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Appendix I

[illegible] BIBLIOGRAPHY OF JOURNAL ARTICLES
[illegible]

P. L. Jackson, "Correlation Function Spatial Filtering with Incoherent Light," Applied Optics, Vol. 6, p. [illegible], July 1967.

> The method of lensless correlography (Meyer-Eppler effect) has been extended to image one of the transparencies which are being correlated. An optical filter is placed in the correlation plane, so that the image of the transparency represents the "time-domain" analog of a complex frequency filter.

P. L. Jackson, "Sectional Correlograms and Convolutions by Simple Optical Method," Geophysics, Vol. 33, No. 5, October 1968.

> Sectional correlograms, which have been shown recently to be interpretively valuable in several ways, can be obtained with a simple optical method. A visual presentation of sectional correlograms can be obtained from variable-density or variable-area record sections. Individual autocorrelations, selected crosscorrelations, or sums of selected correlations can be displayed simultaneously for all channels in a conventional section. The display is economically and simply achieved by using an elaboration of the Robertson technique of optical correlation. A two-dimensional correlation function is obtained with the basic Robertson technique. With the addition of a cylindrical lens and an adjustable slit, many simultaneous selective one-dimensional correlations can be obtained; thus, sectional correlograms with seismic transparencies can be produced. Because a broad band, incoherent light source is employed, this optical method can be used with a pattern on a CRT as data input.

I. K. McIvor, "Scattering of Plane Elastic Waves by Surface Imperfections," Bull. Seism. Soc. Am., Vol. 59, No. 3, pp. 1349-1364, June 1969.

> A perturbation method for treating the scattering of plane waves by small surface imperfections on an elastic half space is presented. The solution to the first order approximation is given as convolution integrals of the surface imperfection with kernel functions defined by Fourier inversion integrals. The evaluation of these integrals is discussed and their asymptotic representations determined. The far field scattered displacements are explicitly obtained for arbitrary imperfections. The scattered field consists of a Rayleigh surface wave and four body phases which at the free surface

[illegible]

[illegible]

[illegible], "A Method of Processing Three-Component Seismic Data with Optical Processors," submitted to Geophysics for publication.

A method is given for placing three-component seismic data on film in a manner that permits processing by optical methods. It is shown theoretically that the diffraction patterns of the "stacked" three-component data indicate certain two-dimensional Fourier plane filters which discriminate against elliptically polarized noise. This noise attenuation is achieved optically by the addition of a vertical seismogram and a horizontal (in the direction of noise propagation) after one has been phase shifted by π/2 with respect to the other. Amplitude equalization during this process is also possible optically.

C. G. Bufe and D. E. Willis, "High Frequency Seismological Energy from Aleutian Sources," Bull. Seism. Soc. Am., Vol. [illegible], No. [illegible], pp. [illegible]-3030, October [illegible].

The Long Shot event, detonated at Amchitka in the Aleutian Islands, was recorded at three sites in Michigan at distances of [illegible] to 61 degrees. Analysis of the data recorded on magnetic tape shows significant high frequency (1-5 Hz) energy in the first compressional wave arrivals at all three stations, although the most prominent spectral peaks are in the range 1.0 to 1.6 Hz. Initial P phases of aftershocks of the Good Friday earthquake of 1964 recorded at the Ann Arbor station do not contain appreciable energy above about 2 Hz. However, the P-wave spectrum of an earthquake of comparable magnitude whose epicenter is near Long Shot is very similar to that of Long Shot, and indicates a favorable signal-to-noise ratio to 5 Hz.

The Long Shot spectra and apparent angle of incidence at the Michigan stations appear to be influenced by the presence of pP and by crustal layering. The effective response of an intermediate-depth well system is shown to be strongly affected by surface reflections.

Leon Reiter, "An Investigation Into the Time Term Method in Refraction Seismology," Bull. Seism. Soc. Am., Vol. 60, No. 1, pp. 1-13, February 1970.

The time term method of seismic refraction data anslysis allows an areal arrangement of shot points and stations and yields directly a three-dimensional representation of underlying structure. This method was investigated analytically and through numerical experiments to determine implicit sources of error and to provide guidelines for its proper use. Error terms for computed refractor depths were derived for two site arrays over two structures, a simply dipping refractor surface and a symmetric anticlinal refractor surface. These error terms proved to be qualitatively reliable guides to the performance of the time term method using models of multi site arrays over planar and biplanar refractor structures. Neither continuity of time terms nor use of a known refractor velocity in the computations offered a guarantee of a more accurate refractor reconstruction. In the two models tested a refractor velocity greater than the true velocity yielded the best reconstruction. Sensitivity to angle of dip indicated preferred orientation of shot-station lines along gentle apparent dips when the underlying structure is known and their orientation along several azimuths when the structure is unknown so as to mute the effect of high dip angles. If the structure has refractor surfaces dipping more than a few degrees, the time term method will give inaccurate results unless previous knowledge of the refractor configuration permits model studies to determine error terms and arrangement of shots and stations. Unfortunately such knowledge is usually the goal of a seismic experiment.

C. G. Bufe and D. E. Willis, "A Note on Short Period Seismic Spectral Ratios," Earthquake Notes, Vol. 40, No. 1, March 1969.

An inverse square frequency dependence of the amplitude ratio of P waves from events differing in yield by several orders of magnitude is shown to exist over several octaves in frequency. The behavior of the spectral ratio of particle velocities for the 12.5 kiloton SHOAL nuclear explosion and 2.5 ton USGS Delta, Utah shot is used to estimate the radius of "equivalent radiator" at SHOAL.

P. L. Jackson, "Seismic Ray Simulation for Spherical Earth," Bull. Seism. Soc. Am., Vol. 60, No. 3, pp. 1021-1025, June 1970.

This letter describes a method of ray simulation to relate velocity distribution to travel times in spherical earth which also is based upon Snell's law of refraction with the addition of the law of reflection. Given a velocity distribution, travel times for all exclusively P or S phases of body waves can be generated and a predetermined number of multiple reflections included. No restrictions exist upon the positive or negative values of dv/dr or upon discontinuities in the velocity distribution. Tables, mathematical functions, or combinations of both are used to refer to the velocity distribution. Mathematical functions can be used within depth ranges where it is convenient to represent the distribution mathematically; tables in depth ranges with abrupt or anomalous distributions, or where one desires to alter specific velocity values when repeating the tracing of a ray.

D. E. Willis and J. T. Wilson, "A Note on the Anna, Ohio Earthquake of July 26, 1968," submitted for publication to Earthquake Notes, July 1970.

A small earthquake located near Anna, Ohio was recorded on the University of Michigan's special well system on July 26, 1968. The body wave magnitude was determined to be 3.0 with a modified Mercalli intensity of at least III. Spectral analyses showed that most of the seismic energy was contained in a band from 3 to 10 Hz.

Appendix II

CHRONOLOGICAL ANNOTATED BIBLIOGRAPHY OF TECHNICAL REPORTS
SPONSORED BY AF49(638)-1759

David E. Willis and Philip L. Jackson, Collection and Analysis of Seismic Wave Propagation Data (Annual Report), Rept. No. 8071-6-P, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, August 1967.

This report summarizes one year of theoretical and applied research on propagation of seismic waves and techniques for analyzing data. The main objectives were to determine the frequency and energy of seismic signatures, and investigate attenuation, patterns of azimuthal radiation from source regions, and methods of determining the type of motion at the source. Natural and artificial sources were studied to develop diagnostic aids for distinguishing between earthquakes and underground nuclear detonations. Equipment for selection, reformatting, and digital-to-analog conversion for digitally recorded LASA data was constructed and is being checked out. Several approaches for using the parallel computational capabilities of optics for LASA data were developed. A study of background noise and reciprocity for teleseismic events as recorded on the bottom of a large fresh water lake has commenced with the emplacement of three-component seismometers in Lake Superior. Array data have been used for crustal studies on the Eastern United States. Digital mode filtering was investigated. A perturbation theory for seismic sources was developed.

David E. Willis, An Investigation of Seismic Wave Propagation in the Eastern United States, Rept. No. 8071-16-T, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, July 1968.

This paper describes the travel-time anomalies and attenuation losses of seismic compressional waves generated by a series of underwater explosions in the Eastern United States. The efficient tamping of the shots fired in water provided a seismic source that could be detected at much larger ranges than could be accomplished by equivalent sized shots fired underground.

A number of mobile field recording stations equipped with three-component matched short period seismometers and magnetic tape recorders were used to record 273 individual shots. A total of 1,295 recordings were obtained along a reversed profile extending from International Falls, Minnesota to the

Atlantic Coast. The underwater shots were fired in Lake Superior and the Atlantic Ocean. Precise travel times were obtained by recording radio time signals at all of the recording stations.

An analysis of the travel-times of the seismic waves disclosed that the earth's crust varies in thickness from 28.1 km near the Atlantic Coast in North Carolina to 50.4 km near the Keweenaw Peninsula in upper Michigan. The crust in North Carolina was found to be comprised of a single layer with a compressional wave velocity of 6.0 km/sec. A two-layer crust with compressional wave velocities of 6.2 and 7.7 km/sec was disclosed in upper Michigan. Travel time residuals across the Appalachian Mts would indicate a mountain root system similar to that found under the Rocky Mts.

The Lake Superior area was found to be more efficient in the coupling of energy into seismic waves by the underwater shots than in the Atlantic Ocean. This is believed due mainly to the bubble pulse phenomenon and the reinforcement caused by reverberation of sound waves between the lake bottom and the water's surface.

A new technique of displaying seismic attenuation data in three dimensional space was developed that permits presentation of large quantities of data in a concise manner, hence aiding in the interpretation of the data. Consistent anomalies in the spectrum of the seismic waves were found that could be correlated with various parameters in the source region and with propagation effects.

The detailed spectral studies that were made as a function of distance from the source disclosed that the attenuation of the seismic waves could be expressed by the equation

$$A = A_o X^{-n} e^{-\alpha f X}$$

where A = amplitude, X = distance, n = geometrical spreading factor, α = absorption coefficient and f = frequency. The crustal attenuation data in the Lake Superior area were found to have a value of n = 1.5 and $\alpha = 2\text{-}3 \times 10^{-3}$. Upper mantle compressional wave attenuation data gave a value of n = 1 and $\alpha = 2 \times 10^{-4}$.

David E. Willis and Philip L. Jackson, Collection and Analysis of Seismic Wave Propagation Data (Annual Report), Rept. No. 8071-15-P, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, September 1968.

This report discusses the results of an extensive long-range reversed refraction profile which traverses the Michigan

Basin and the Appalachian Mountains. Particular emphasis is placed on the attenuation of first compressional wave arrivals and on crustal-upper mantle structure. Also included are results of a survey on lake bottom seismic background noise in Lake Superior. Although large signal levels were obtained in the lake bottom, long periods of high background noise indicated that land based seismographs are superior. Theoretical studies in elastic wave scattering were made to evaluate the effect of nonhomogeneities on the propagation of elastic waves. Theoretical development of mode filtering, (previously demonstrated empirically), is nearly completed. A LASA digital data convertor was designed, constructed, and put into operation. Two- and three-dimensional seismic ray-tracing techniques using digital modeling were developed. These techniques enable the seismologist to determine the effects of lateral inhomogeneities and irregularities in velocity interface on travel time and attenuation of seismic waves.

Philip L. Jackson, Roger M. Turpening, and David E. Willis, Collection and Analysis of Seismic Wave Propagation Data (Annual Report), Rept. No. 8071-25-P, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, July 1969.

The work performed under this contract during the past year included mode filtering, S-wave studies; seismic ray tracing; theoretical studies in elastic-wave scattering; seismic wave propagation near the core-mantle boundary; time term, travel time, spectral, and attenuation studies; and field measurements primarily with an intermediate-depth well seismograph station. Seven journal articles were either published or submitted for publication during this period. Continuation of this contract will be concerned with S-wave studies for difference in arrival times caused by layering at the recording location, simulation by ray tracing to investigate the velocity structure underlying LASA, and a field measurement program of continuous recordings in Nevada.

David E. Willis, Philip L. Jackson, and Roger M. Turpening, Collection and Analysis of Seismic Wave Propagation Data (Semi-Annual Report), Rept. No. 8071-30-L, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, January 1970.

The scope of this contract includes S-wave mode filtering, seismic ray tracing, and microearthquake investigations. After much delay pertinent LASA tapes have been obtained; the LASA data processor has been interfaced with the PDP-8/I computer located in the Geophysics Laboratory to perform the S-wave mode filtering.

Highly accurate seismic ray simulation through two-dimensional heterogeneous velocity distributions has been achieved, and the extension to three dimensions with selective regions for sampled or mathematically represented data is being programmed. Preliminary analysis of seismograms recorded before and after the JORUM underground nuclear explosion indicate that there was no significant difference in the occurrence of local microearthquakes before and after this explosion.

Charles G. Bufe, An Estimate of the Configuration of the Surface of the Earth's Core from the Consideration of Surface Focus PcP Travel Times, (PhD Dissertation) and (Supplement to 8071 Final Report), Rept. No. 8071-33-F_2, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, July 1970.

Travel times of PcP and P phases from nuclear and high explosive sources are interpreted in terms of variations in the radius of the earth's outer core. Travel-time residuals from the Taggart-Engdahl (1968) tables are determined for the PcP-P time interval and for PcP travel times, corrected for station and source terms. The travel times are also corrected for elevation of source and station and ellipticity, excluding the core ellipticity term. This interpretation favors a core which is slightly larger than that of the reference model of Taggart and Engdahl (1968) and which has less ellipticity than estimated by Bullen (1936). Other interpretations in terms of lateral variation in mantle velocity are also possible.

Because all of the events and most of the stations whose data are used lie in the northern hemisphere, the description of core shape is incomplete and is representative only of regions of the core surface in the vicinity of the PcP reflection points.

The distribution of data does not permit a conventional spherical harmonic analysis of the inferred variation in core radius. A modified spherical harmonic analysis method is devised to smooth the data and to estimate the shape of the core. The variation of core radius determined from this representation is approximately ±10 kilometers on the basis of terms to degree and order 5. The standard deviation of the data is approximately ±20 kilometers, indicating the presence of variations of higher degree and order, many of which are probably due to factors other than undulation of the mantle-core boundary. Variations in geoid height resulting from the inferred variations in core radius do not correlate with, but are of the same order of magnitude as, those determined from satellite observations.

Analysis of a limited number of short-period PcP amplitudes shows no significant variation of the PcP amplitude/period ratio with epicentral distance and an estimated scatter of data on the same order as that found for P in the distance range 70° to 90°. The PcP phase is generally shorter in apparent period than the P phase. This relationship is reversed, however, for arrivals from the Novaya Zemlya event of October 27, 1966.

The contribution of a hypothetical upper mantle low velocity zone of varying thickness to the amplitude and travel-time scatter is demonstrated.

Philip L. Jackson, Digital Simulation of Seismic Rays (PhD Dissertation) and (Supplement to 8071 Final Report), Rept. No. 8071-33-F_1, Willow Run Laboratories of the Institute of Science and Technology, Geophysics Laboratory, The University of Michigan, Ann Arbor, July 1970.

Simulation of seismic rays for a spherical earth and a flat earth has been achieved in highly complex models. Travel times and approximate amplitudes of seismic waves can be found for both two- and three-dimensional models of portions of the earth. Hypotheses of complicated and detailed velocity distributions within the earth can be tested by comparing travel times found in models with travel times found from actual earthquakes and explosions.

Since ancient times rays have been constructed to denote the direction in which energy is propagating. As in other scientific fields, the construction of rays to represent propagation paths has been a fundamental technique of modern seismology since its inception in the latter part of the 19th century. In seismology and other disciplines ray construction has been applied to simplified geometries. It has been necessary to assume that the seismic wave velocity distribution of the earth was relatively uniform and symmetric.

Recently, however, the earth has been found to be more complex and non-uniform than formerly assumed. Travel times have been extensively measured with more accurate instrument techniques, making historical methods of ray construction inadequate for either visualization of the rays or numerical indication of expected travel times. A need has thus arisen in seismology to test highly heterogeneous models of seismic velocity distribution. At the same time the development of the modern digital computer has provided a means of performing the necessary ray constructions and numerical calculations.

The problem of complicated seismic velocity distributions was therefore investigated in terms of the most appropriate use of the digital computer. For this investigation a velocity field was set up, and the propagation computations made for short segments of rays within this field. For each segment the surrounding parameters of propagation were known, hence changes in direction and time of travel could be computed, and newly computed segments joined to those preceding until a complete ray is constructed. The total travel times are also found by adding the travel times of all the joined ray segments. Essentially, the nature of propagation was duplicated on the computer, in that, at the location of each segment along the path of propagation, the initial condition and effect of the surroundings determine the succeeding direction of the following segment.

Both visual and numerical results have shown that this simulation method can be usefully applied to investigation of seismic velocity distributions of portions of the earth of any size or complexity. Computer drawn plots of the entire spherical earth, and on vertical cross-sections of the underlying structure across California and of typical lithospheric plate boundaries illustrate useful applications of this method. Accuracy is illustrated by calculation of essentially the same travel times for P waves as published by the Seismological Society of America.

David E. Willis and Robert F. Hand, Seismic Measurements of DIAMOND DUST (Supplement to 8071 Final Report), Report No. 8071-33-F_3/3620-1-T, Willow Run Laboratories of the Institute of Science and Technology, The University of Michigan, Ann Arbor, July 1970.

A small nuclear device detonated in an underground cavity was recorded at five close-in sites. Portable stations were located to study azimuthal effects. Strong asymmetries were observed in frequency content, amplitude and wave train duration. These effects can be explained in part by the variations in geology at the recording sites. However, source radiation could account for some of the observed anomalies.

Appendix III

CHRONOLOGICAL ANNOTATED BIBLIOGRAPHY OF SCIENTIFIC PRESENTATIONS PREPARED UNDER SPONSORSHIP OF CONTRACT AF49(638)-1759

D. E. Willis and J. T. Wilson, "A Long-Range Reversed Seismic Profile in the Eastern United States," presented at the International Union of Geodesy and Geophysics, XIVth General Assembly, Switzerland, September 25 through October 7, 1967.

A series of underwater high-explosive shots fired during the past five years have provided data for a reversed seismic profile approximately 2000 km in length. These shots include the 1962 offshore North Carolina experiment, the 1965 ECOOE series, the CHASE III, IV, and VII events, and the Lake Superior shots of 1963, 1964, and 1966. Close station intervals were obtained along the profile. Travel-time curves, frequency analyses and attenuation measurements are presented for these recordings. An intermediate crustal layer with a velocity of 7.7 km/sec was disclosed on the northwestern portion of this profile. Higher P_n velocities and a thicker crust was also indicated. Smaller travel time residuals across the Michigan Basin were observed on both profiles. The travel-time data indicated a possible mountain root system under the Appalachians. Contoured particle-velocity maps made from the spectral data disclosed amplitude anomalies that could be correlated with conditions in the source region. These results aid in the interpolation of the attenuation data.

C. G. Bufe and D. E. Willis, "Seismic Radiation from SHOAL," presented at the 64th Annual Meeting of the Seismological Society of America, Tuscon, Arizona, April 11-13, 1968.

Travel times and particle velocities have been examined for distances to 1600 km and for widely distributed azimuths for the SHOAL event. A composite curve of raw travel-time data reaffirms the anomalously low P_n velocities previously observed in the Basin and Range province and yields a crustal thickness of about 26 km. Particle velocities were measured for 3 sets of 3 stations each at distances of 250, 320, and approximately 1100 km. The particle velocity spectra vary widely from site to site and generally reflect characteristics of the spectra of the seismic background at each site.

David E. Willis, "Seismic Noise on the Bottom of Lake Superior," presented at the 49th Annual Meeting of the American Geophysical Union, Washington, D. C., April 8-11, 1968.

A series of seismic background noise measurements were made on the bottom of Lake Superior during June-August 1967. The measurements were made at the site of the 1966 Lake Superior shot point in approximately 575 feet of water. Two instrument packages that were obtained on loan from the University of California were used for these measurements. Each was equipped with three-component, short-period seismometers, a magnetic tape recorder, and an accurate chronometer. One free-fall drop and three tethered drops were made. Approximately ten days of continuous recordings were obtained for each of three time periods, the last of which included a tethered unit and a free-fall unit. The background noise was found to be quite high, averaging in the vicinity of 100 mμ at 1 cps. Long periods lasting up to several days of extremely high background noise were noted. These periods could be correlated with wave action and meteorological conditions. At their peaks, ground displacements of the order of 3000 mμ were observed. Several earthquakes were recorded during this period as well as many quarry shots. Spectral analyses of these events are correlated with data obtained from a station operated nearby on land. Comparisons of signal-to-noise ratios are also presented.

Philip L. Jackson, "Two- and Three-Dimensional Ray Tracing, Travel Time, and Amplitude Computation," presented at the 64th Annual Meeting of the Seismological Society of America, Tuscon, Arizona, April 11-13, 1968.

Seismic rays can be traced through velocity and density structures of any degree of inhomogeneity. A digital computer is used to trace and graphically to present the rays, and to compute the travel times and amplitudes of those emerging at the surface. The number of multiple reflections can be selected or can be limited by a minimum amplitude upon reflection. A sampling of the structure on two- or three-dimensional grids comprises the data for the ray tracing. As the data can be "patched" together and the continuation of rays traced through each data "patch," only a small amount of computer memory is required; thus, detail is not limited by computer memory. Calcomp plots of ray traces through several representative velocity structures have been made. Included is an earth quadrant in which the Jeffreys-Bullen P-wave velocity profile was used for data. The program can be extended to include more techniques of seismic interest, such as Zoeppritz's equations, head waves, Rayleigh waves, and so forth. The goal of this work is to present the output on a cathode-ray tube so that the results of velocity and density data changes can be immediately perceived.

Philip L. Jackson, "Seismic Ray Simulation," presented at the Eastern Section, Seismological Society of America Meeting, Blacksburg, Virginia, October [illegible], 1969.

A continuing development of ray simulation by digital computer has resulted in highly accurate travel times through sampled velocity fields. Seismic rays are traced by direct simulation. Rays are "propagated" through a representation of a velocity field using iterations of Snell's law. The velocity field has no limitations as to discontinuities or slopes, and can be referenced by a mathematical function of the position along the ray, by a two- or three-dimensional matrix corresponding to the position, or by lookup from a table with subsequent computation. Multiple reflections are performed between interfaces with predetermined velocity differences. A flat or curved earth can be employed with point or extended sources. All types of P phases have been traced and plots have been drawn by computer. For curved earth the travel times converge to those of the 1968 Seismological Tables for P phases when sampling the velocity distribution upon which the 1968 tables are based. Examples of both extended and point sources will be shown in addition to movies of the propagation of various core phases. This simulation approach can be extended to include mode conversion.

C. C. [illegible] and D. E. Willis, "Near Earthquake Spectra," presented at the Annual Meeting of the Seismological Society of America, Hayward, California, April 1970.

Spectra of P and S phases of microearthquakes at hypocentral distances less than 25 km are presented for a number of seismically active regions. Spectral ratios of events of different magnitude but similar in mechanism and propagation path are also presented in order to isolate the influence of source dimension, seismic moment, etc., on the spectra. At distances of 20 to 25 km, maximum particle velocities generally occur in the range 12.5 Hz to 40 Hz for P and 10 Hz to 20 Hz for S. Spectra of events recorded in central California near Hollister are generally anomalous in their absence of high frequencies. However, one such event, recorded by a second station at a hypocentral distance of less than 10 km, shows appreciable energy to 50 Hz. A very low Q (near 10) and/or considerable scattering of high frequency waves in the vicinity of the San Andreas fault zone could account for these observations. Consequences would be the underestimation of magnitude of microearthquakes and the apparent absence of very small events unless they occur very near the station.

David E. Willis, "Microearthquake Studies in Connection with the JORUM Underground Nuclear Detonation," for presentation at the GSA/SSA Annual Meeting to be held in Milwaukee, November 11-14, 1970.

A tripartite net of three-component portable short-period seismograph stations was operated continuously for two weeks prior and three weeks after the JORUM underground nuclear shot of September 17, 1969. These stations were located 60 to 100 km from the source near active faults. No significant changes were observed in local microseismic activity before and after the event indicating the shot did not cause any release in tectonic energy in the vicinity of the temporary stations. The wideband frequency response of the recording systems allowed the detection of local events that contained high frequency energy which peaked as high as 90 Hz. At one station a pronounced diurnal effect in the occurrence of these high frequency events was observed.

David E. Willis, "Azimuthal Asymmetries Observed Around a Point Source," for presentation at the GSA/SSA Annual Meeting to be held in Milwaukee, November 11-14, 1970.

The Geophysics Laboratory at The University of Michigan operated five short-period seismograph stations to record a low-yield underground nuclear shot fired at the Nevada Test Site. The shot was fired in an air-filled cavity to test the feasibility of thermo-mechanical techniques for decoupling seismic energy. Four stations were located at approximately 2.5 km to study the azimuthal effect. The fifth station was located at 6.14 km to provide attenuation data. Strong asymmetries were observed in frequency content, amplitude and wave train duration. The complicated local geology could explain, in part, the observed anomalies. However, at the present time, some source radiation effects cannot be discounted.

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13 ABSTRACT

A new method of simulating seismic rays, computing travel times, and approximating amplitudes in earth models has been developed. The digital computer is used to model a spherical or a flat earth. Two- or three-dimensional models are employed. The method can be used for heterogeneous models, and includes computation of multiple reflections. Travel times have been obtained for a model of a cross-section underlying LASA.

In 1967 the investigation of optical processing was terminated. Initiated in 1961, the investigation was conducted to explore the application of coherent optical processing to seismic analysis. Its use was found to lie primarily in oil exploration seismology.

A data processing capability specifically intended for the study of the S-wave particle variations across LASA was built on this contract. The LASA data processor, which existed in this laboratory for the optical analyses of LASA data, was modified to interface with this laboratory's PDP-8 computer. This data processing capability was not used due to funding limitations.

Microseismic investigations in connection with JORUM indicated that the firing of a large yield underground shot did not produce any measurable tectonic release of energy in active fault regions at a distance of 60 to 100 km from the source. Seismic measurements of DIAMOND DUST indicated decoupling was achieved but the accurate determination of the efficiency of the decoupling will have to be determined by additional tests. A pronounced asymmetry in seismic wave characteristics was observed.

Travel time studies of PcP and P were used to determine the surface configuration of a portion of the earth's core. An extensive study was made on the attenuation and travel times of seismic waves in the Eastern United States. Theoretical studies were made to determine the scattering effects of plane elastic waves by surface imperfections and to determine the sources of error in the time-term method in refraction seismology.

Spectral studies were made of underground nuclear shots and earthquakes recorded at teleseismic, regional and near distances. An additional study was made of the characteristics of seismic background noise recorded on the bottom of Lake Superior.

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